

Recent developments in SHERPA

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Institute for Particle Physics Phenomenology

QCD@LHC, 21/08/2012



[arXiv:1111.1220](#), [arXiv:1207.5030](#)

[arXiv:1207.5031](#), [arXiv:1208.2815](#)

LHCphenOnet



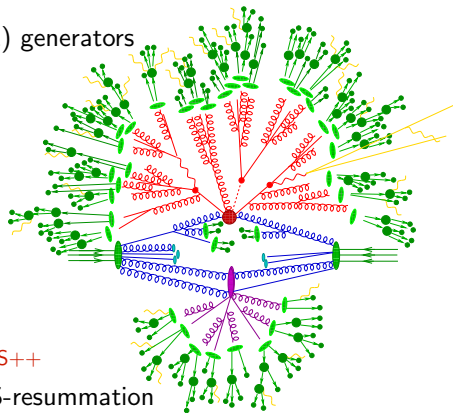
The SHERPA event generator framework

- Two multi-purpose Matrix Element (ME) generators
AMEGIC++ JHEP02(2002)044
COMIX JHEP12(2008)039
- A Parton Shower (PS) generator
CSSHOWER++ JHEP03(2008)038
- A multiple interaction simulation
à la Pythia **AMISIC++** hep-ph/0601012
- A cluster fragmentation module
AHADIC++ EPJC36(2004)381
- A hadron and τ decay package **HADRONS++**
- A higher order QED generator using YFS-resummation
PHOTONS++ JHEP12(2008)018

Sherpa's traditional strength is the perturbative part of the event

MEPs (CKKW), Mc@NLO, MENLOPs, MEPS@NLO

→ QCD-NLO calculations through automated CS-subtraction EPJC53(2008)501



Mc@NLO

Frixione, Webber JHEP06(2002)029

$$\begin{aligned}
 \langle O \rangle^{\text{NLO+PS}} = & \int d\Phi_B \bar{B}^{(A)}(\Phi_B) \left[\Delta^{(A)}(t_0, \mu_Q^2) O(\Phi_B) \right. \\
 & \left. + \int_{t_0}^{\mu_Q^2} d\Phi_1 \frac{D^{(A)}(\Phi_B, \Phi_1)}{B(\Phi_B)} \Delta^{(A)}(t, \mu_Q^2) O(\Phi_R) \right] \\
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 \end{aligned}$$

Höche, Krauss, MS, Siegert arXiv:1111.1220

- NLO weighted Born configuration $\bar{B}^{(A)} = B + \tilde{V} + I + \int d\Phi_1 [D^{(A)} - D^{(S)}]$
 - use $D_i^{(A)}$ as resummation kernels $\Delta^{(A)}(t, t') = \exp \left[\int_{t'}^t d\Phi_1 D^{(A)}/B \right]$
 - resummation phase space limited by $\mu_Q^2 = t_{\text{max}}$
 - starting scale of parton shower evolution
 - should be of the order of the hard resummation scale
 - ⇒ first implementation to allow to study μ_Q uncertainty

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every term is well defined and NLO and NLL accuracy maintained if:

- $D^{(A)} = \sum_i D_i^{(A)}$ is full colour correct in soft limit
- $D^{(A)} = \sum_i D_i^{(A)}$ contains all spin correlations in collinear limit
- $D_i^{(A)}$ and $D_i^{(S)}$ have identical parton maps

\Rightarrow **conventional parton showers need to be improved for that**

e.g. choose $D_i^{(A)} = D_i^{(S)}$ up to phase space constraints

Case study: Inclusive jet & dijet production

Describe wealth of experimental data with a single sample (LHC@7TeV)

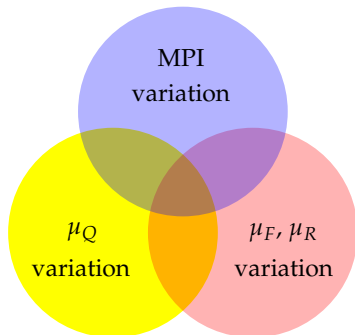
MC@NLO di-jet production:

Höche, MS arXiv:1208.2815

- $\mu_{R/F} = \frac{1}{4} H_T$, $\mu_Q = \frac{1}{2} p_{\perp}$
- CT10 PDF ($\alpha_s(m_Z) = 0.118$)
- hadron level calculation
fully hadronised including MPI
- virtual MEs from BLACKHAT
Giele, Glover, Kosower
Nucl.Phys.B403(1993)633-670
Bern et.al. arXiv:1112.3940
- $p_{\perp}^{j1} > 20$ GeV, $p_{\perp}^{j2} > 10$ GeV

Uncertainty estimates:

- $\mu_{R/F} \in [\frac{1}{2}, 2] \mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}] \mu_Q^{\text{def}}$
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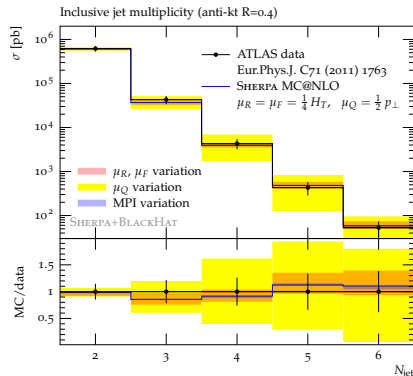
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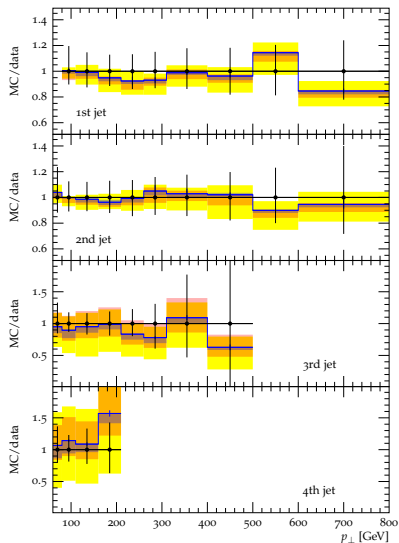
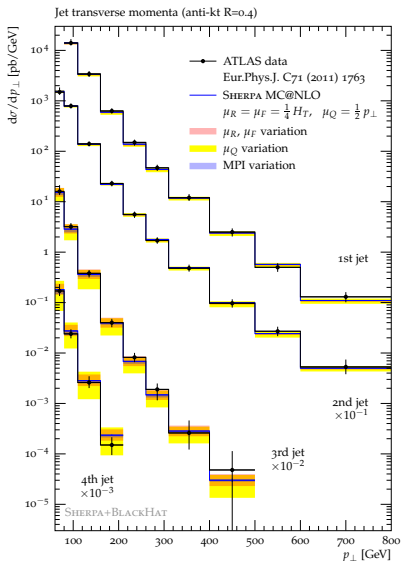
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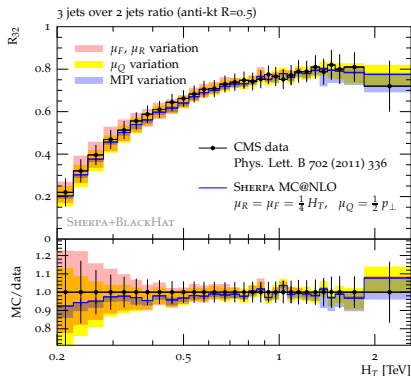
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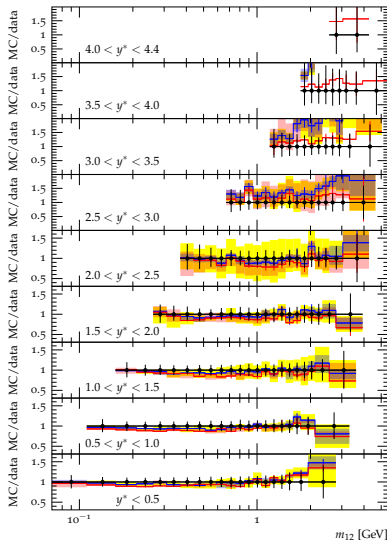
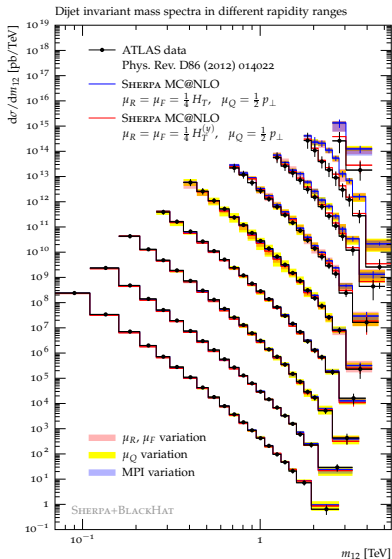


3-jet-over-2-jet ratio

- determined from incl. sample
2-jet rate at NLO+NLL
3-jet rate at LO+LL
- common scale choices
→ varied simultaneously
- at large H_T large MPI uncertainties
→ better MPI physics needed (soft QCD)
- similar description of related ATLAS observables

Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815



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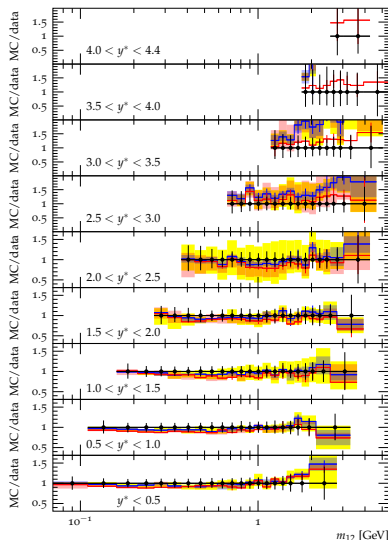
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Try different scale

- $\mu_{R/F} = \frac{1}{4} H_T^{(y)}$ with
 $H_T^{(y)} = \sum_{i \in \text{jets}} p_{\perp, i} e^{0.3|y_{\text{boost}} - y_i|}$
 with $y_{\text{boost}} = 1/n_{\text{jets}} \sum_{i \in \text{jets}} y_i$
- reduces to $\mu_{R/F} = \frac{1}{2} p_{\perp} e^{0.3y^*}$
 with $y^* = \frac{1}{2}|y_1 - y_2|$ for $2 \rightarrow 2$
 and captures real emission dynamics
[Ellis, Kunszt, Soper PRD40\(1989\)2188](#)
- better description of data at large rapidities, as expected

description of most other observables worsened

need proper description of forward physics (e.g. (B)FKL)



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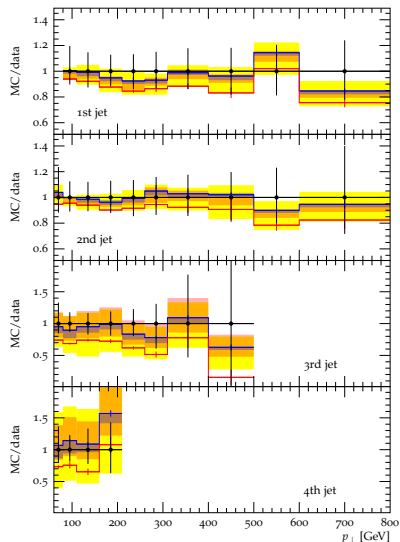
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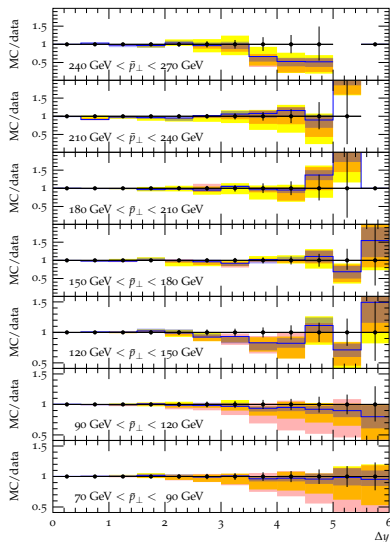
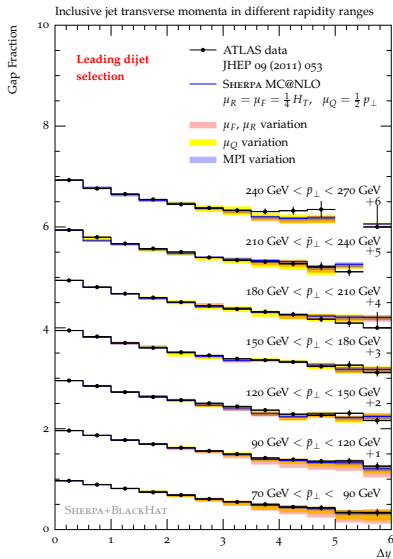
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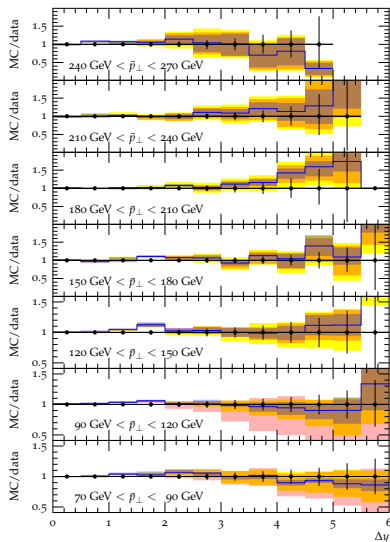
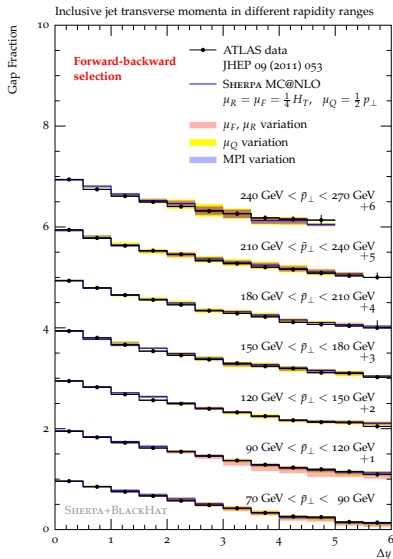
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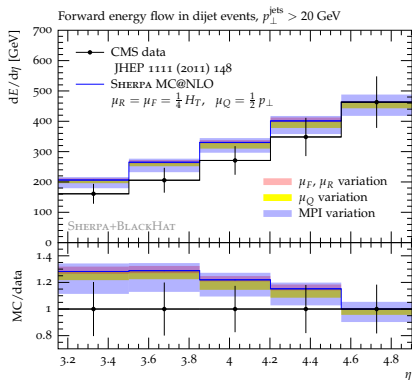


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Forward energy flow

- energy flow in rapidity interval per event with a central back-to-back di-jet pair
- normalisation reduces $\mu_{R/F}$ and μ_Q dependence
- dominated by MPI modeling uncertainty

NLO merging

LO merging:

- LO accuracy for $n \leq n_{\text{max-jet}}$ processes
- preserve LL accuracy of the parton shower

Catani, Krauss, Kuhn, Webber JHEP11(2001)063

Lönnblad JHEP05(2002)046

Höche, Krauss, Schumann, Siegert JHEP05(2009)053

Hamilton, Richardson, Tully JHEP11(2009)038

Lönnblad, Prestel JHEP03(2012)019

NLO merging:

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Lavesson, Lönnblad JHEP12(2008)070

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031

NLO merging

$\langle O \rangle^{\text{MEPS@NLO}}$

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$$\begin{aligned}
 &= \int d\Phi_n \bar{B}_n^{(A)} \left[\Delta_n^{(A)}(t_0, \mu_Q^2) O_n \right. \\
 &\quad \left. + \int_{t_0}^{\mu_Q^2} d\Phi_1 \frac{D_n^{(A)}}{B_n} \Delta_n^{(A)}(t_{n+1}, \mu_Q^2) \Theta(Q_{\text{cut}} - Q) O_{n+1} \right] \\
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NLO merging

Renormalisation scales:

- determined by clustering using PS probabilities and taking the respective nodal values t_i

$$\alpha_s(\mu_R^2)^k = \prod_{i=1}^k \alpha_s(t_i)$$

- change of scales $\mu_R \rightarrow \tilde{\mu}_R$ in MEs necessitates one-loop counter term

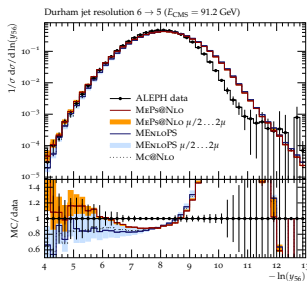
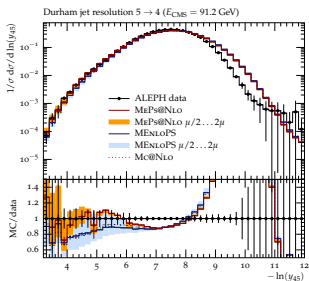
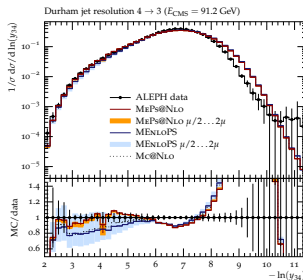
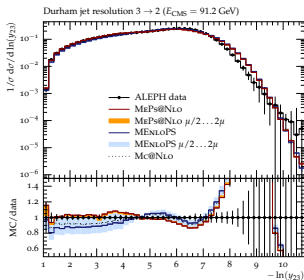
$$\alpha_s(\tilde{\mu}_R^2)^k \left(1 - \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi} \beta_0 \sum_{i=1}^k \ln \frac{t_i}{\tilde{\mu}_R^2} \right)$$

Factorisation scale:

- μ_F determined from core n -jet process
- change of scales $\mu_F \rightarrow \tilde{\mu}_F$ in MEs necessitates one-loop counter term

$$B_n(\Phi_n) \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi} \log \frac{\mu_F^2}{\tilde{\mu}_F^2} \left(\sum_{c=q,g}^n \int_{x_a}^1 \frac{dz}{z} P_{ac}(z) f_c(x_a/z, \tilde{\mu}_F^2) + \dots \right)$$

Results: $e^+e^- \rightarrow$ hadrons



$ee \rightarrow$ hadrons
(2,3,4 @ NLO;
5,6 @ LO)

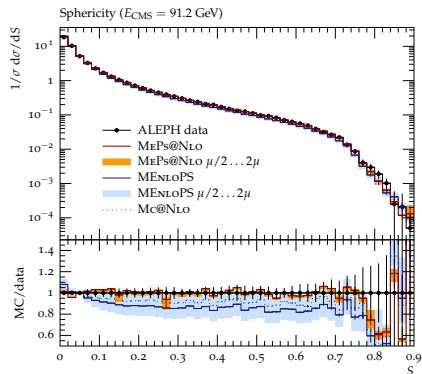
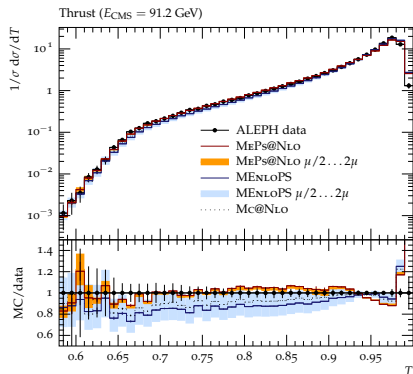
Jet resolutions
(Durham measure)

- MEPS@NLO vs MENLOPS
- at $y \ll 1$ dominated by hadr. effects \rightarrow needs retuning
- much improved ren. scale dependence

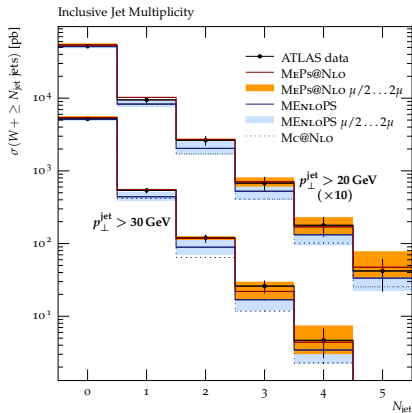
ALEPH data
EPJ35(2004)457-486

Results: $e^+e^- \rightarrow \text{hadrons}$

ALEPH data EPJC35(2004)457-486



Results: $pp \rightarrow W + \text{jets}$

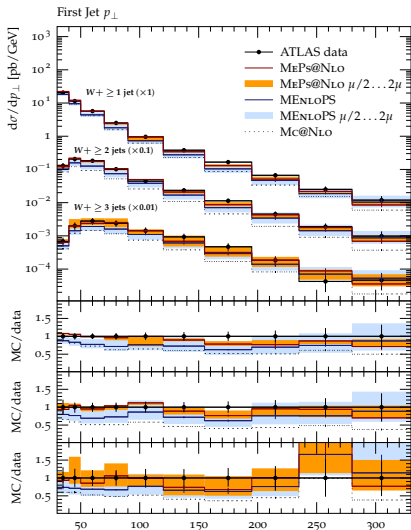


$pp \rightarrow W + \text{jets}$ (0,1,2 @ NLO; 3,4 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2] \mu_{\text{def}}$
scale uncertainty much reduced
- NLO dependence for $pp \rightarrow W + 0,1,2$ jets
LO dependence for $pp \rightarrow W + 3,4$ jets
- $Q_{\text{cut}} = 30 \text{ GeV}$
- good data description

ATLAS data Phys.Rev.D85(2012)092002

Results: $pp \rightarrow W + \text{jets}$



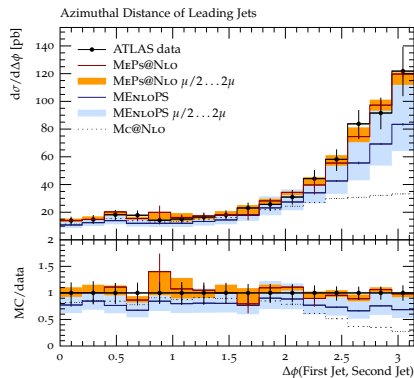
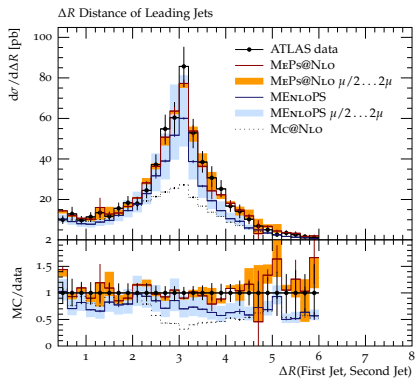
$pp \rightarrow W + \text{jets}$ (0,1,2 @ NLO; 3,4 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2] \mu_{\text{def}}$
scale uncertainty much reduced
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ATLAS data Phys.Rev.D85(2012)092002

Results: $pp \rightarrow W + \text{jets}$

ATLAS data Phys.Rev.D85(2012)092002



Massive quark + vector boson production

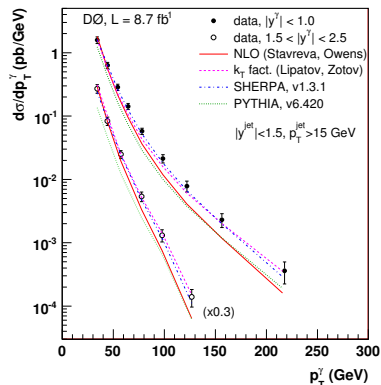
MEPS with massive quarks

- $m_b, m_c \neq 0$
- no conceptual problem
- take massive quarks also into initial state (5 flavour PDFs)
- factorisation of massive initial state á la ACOT
- consistent ME and PS
- merging still only one parameter procedure (Q_{cut})

same as MEPS with massless quarks

available since SHERPA-1.3.0

$pp \rightarrow \gamma + b\text{-jet production}$



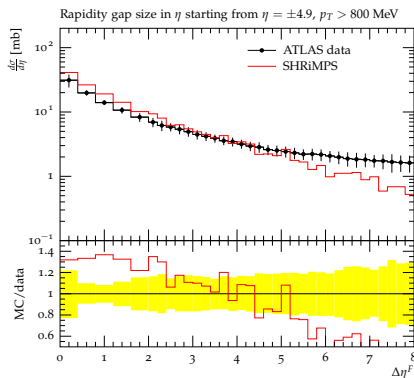
[DØ data arXiv:1203.5865](https://arxiv.org/abs/1203.5865)

Soft QCD – SHRiMPS – KMR model

Soft & Hard Reactions involving Multiple Pomeron Scattering

Krauss et.al. in preparation

- minimum bias and underlying event model based on KMR model
Ryskin, Khoze, Martin
EPJC60(2009)249-264
- KMR model: multi-channel eikonal with partonic interpretation of pomeron
- describes soft & semi-hard QCD, diffraction, elastic scattering and cross sections
- **not tuned yet**



ATLAS data arXiv:1201.2808

Conclusions

- SHERPA's MC@NLO formulation allows full evaluation of perturbative uncertainties (μ_F, μ_R, μ_Q)
 - MC@NLO can be easily combined with MEPS \rightarrow MENLOPs
 - MC@NLO is a necessary input for NLO merging \rightarrow MEPS@NLO
 - MEPS@NLO gives full benefits of NLO calculations (scale dependences, normalisations) while also retaining full (N)LL accuracy of parton shower
- \Rightarrow will be included in next major release

Current release: SHERPA-1.4.1

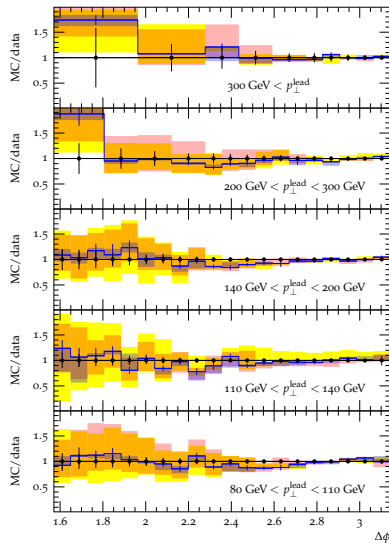
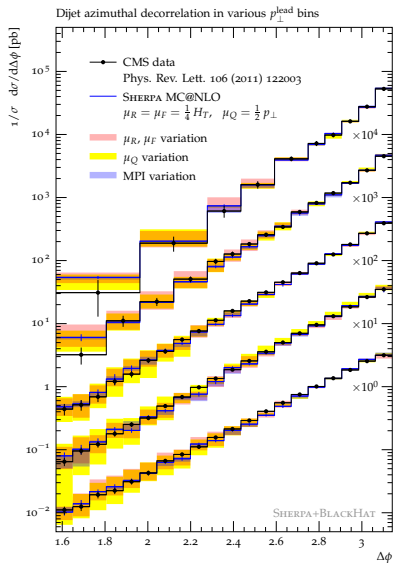
<http://sherpa.hepforge.org>

- precise theoretical calculations need to be confronted with data as differentially as possible over as large a phase space as possible
- good examples: multi-differential cross sections, gap fractions, energy/particle flows, multi-particle/subleading particle correlations

Thank you for your attention!

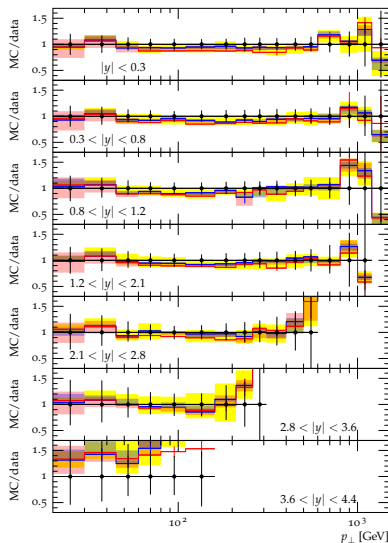
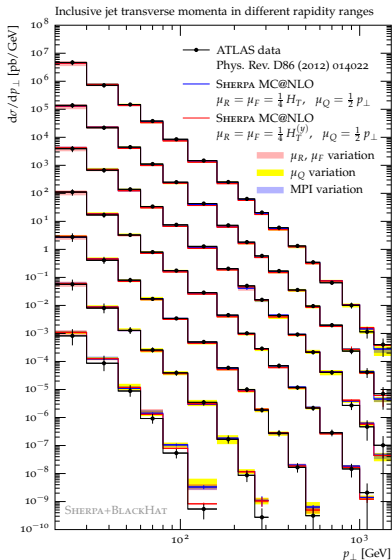
Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815



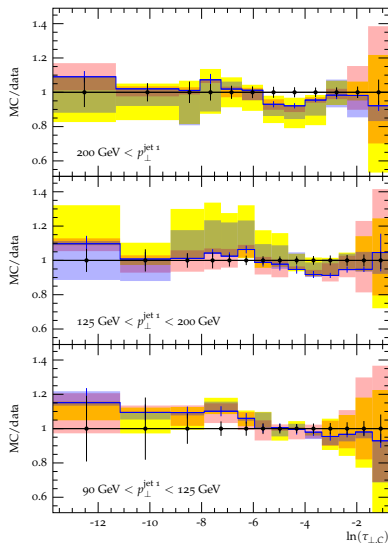
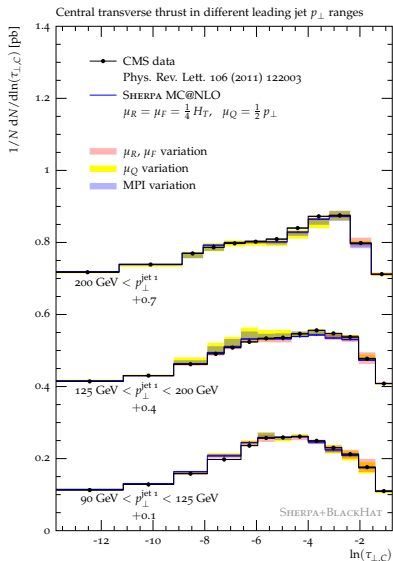
Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815



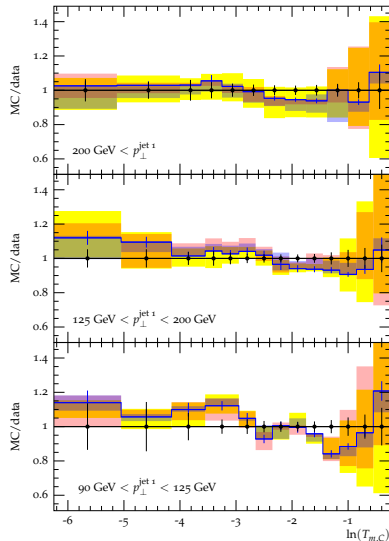
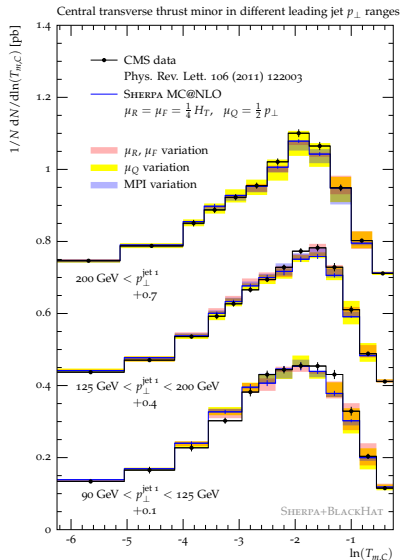
Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815



Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815



NLO merging – Generation of MC counterterm

$$\left[1 + \frac{B_{n+1}}{\bar{B}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} d\Phi_1 K_n \right]$$

- same form as exponent of Sudakov form factor $\Delta_n^{(PS)}(t_{n+1}, \mu_Q^2)$
- truncated parton shower on n -parton configuration underlying $n + 1$ -parton event
 - 1 no emission \rightarrow retain $n + 1$ -parton event as is
 - 2 first emission at t' with $Q > Q_{\text{cut}}$, multiply event weight with $B_{n+1}/\bar{B}_{n+1}^{(A)}$, restart evolution at t' , do not apply emission kinematics
 - 3 treat every subsequent emission as in standard truncated vetoed shower
- generates

$$\left[1 + \frac{B_{n+1}}{\bar{B}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} d\Phi_1 K_n \right] \Delta_n^{(PS)}(t_{n+1}, \mu_Q^2)$$

\Rightarrow **identify $\mathcal{O}(\alpha_s)$ counterterm with the emitted emission**